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ABSTRACT

A PREVIOUS PAPER (1*), reported on fuel consumption reductions achieved, by the use of a Regenerative Power Train system, applied to a city bus.

An overall fuel economy gain of 20% was obtained previously, on the track, when operating the bus on the City Business District cycle (2) [CBD cycle, 20 mph maximum speed and 7 stops per mile], and a similar 30 mph cycle.

The results reported here, were obtained using a CBD type driving cycle and indicate the extent of the reductions in regulated diesel exhaust emissions, achievable with a Regenerative Power Train.

NOx was reduced 19 percent somewhat in line with the percentage improvement in fuel economy; particulate and CO emissions were more strongly influenced, with reductions of 27 and 60 per cent, respectively. HC emissions were the least affected with a reduction of 8 percent.

INTRODUCTION

The particular Regenerative Power Train used here, illustrated in fig. 1, provides vehicle retardation by use of an hydraulic pump, with energy storage taking place within conventional piston accumulators. During a subsequent acceleration, the stored energy, is used to power the hydraulic pump/motor which provides a tractive effort supplementing that generated by the Diesel engine. The net effect is that during the acceleration phase, the diesel engine operates at a lower load level, than is required on a conventional vehicle, to provide a given vehicle performance.

* Numbers in parentheses designate references at end of paper.

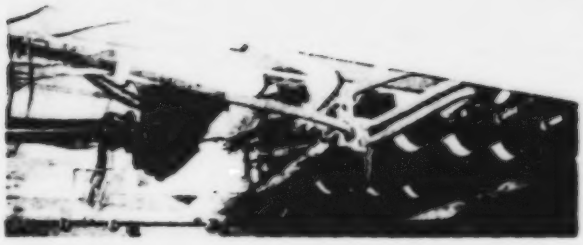

FIG. 1 REGENERATIVE POWER TRAIN INSTALLATION

Tests were conducted in the Exhaust Emissions Laboratory of the SouthWest Research Institute using a CBD type driving cycle. The facilities employed, included a chassis dynamometer with selectable inertia wheels, and an exhaust analysis system comprising a single (total exhaust) dilution, CVS system, with particulate and gaseous emission measurement capability. (3)

Increases in vehicle fuel economy were accompanied by reductions in each of the regulated emissions.

TEST VEHICLE

ORION I - 35 ft. transit bus equipped with 39 seats. 1984 model fig. 2
Engine: Detroit Diesel 6V-71 N (7E60 Injectors)
Transmission: Allison HT747 (TC470) 2nd gear start. N.R.C. design, Regenerative Power Train. (4) (5)
Fuel: Phillips 66 No. 2 Emissions Reference Fuel

FIG. 2 ORION I TRANSIT BUS

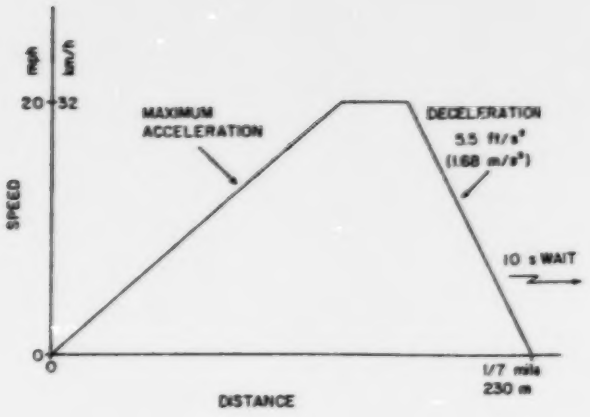

FIG. 3 CBD DRIVING CYCLE

TEST PROCEDURE

The vehicle was installed on the dynamometer rolls with physical inertia discs, simulating the vehicle mass.

The bus was operated according to the CBD phase of the Advanced Design Bus Drive cycles, using a service level deceleration of 5.5 ft/sec^2 (1.68 m/s^2, and a 10 second idle period between successive cycles fig. 3.

Emissions were constartly sampled over a 2 mile run of the cycle.

The cycle average fuel economy was determined by the carbon balance technique, using emissions measurements of HC, CO and CO_2.

To facilitate comparison, the bus was tested in two configurations; with the Regenerative Power Train operational, and secondly, as a standard vehicle. [Mechanical drives to the regenerative system completely disconnected.]

In practice, the Regenerative Power Train would add some 2000 lbs to the vehicle weight, this was reflected in the total inertia weights utilised on the dynamometer.

ANALYTICAL PROCEDURES

The 17.4 m x 1.17 m dia. (57 ft. x 46 ins. dia.) single dilution CVS was used to obtain mass proportional emission samples.

Total hydrocarbons and NOx were determined over each test cycle by integration of the CVS diluted exhaust gas concentrations.

Concentrations of CO and CO_2 were determined from CVS dilute exhaust sample bags.

Emission levels were processed along with the CVS flow parameters and dynamometer parameters, to compute mass emissions and fuel consumption on the basis of distance covered.

DISCUSSION OF RESULTS

Excellent repeatability of measurements was obtained from these laboratory tests, as is evident in tables I and II.

Over a short time interval however, relatively large variations in the emissions performance can be observed. Referring to table I and comparing runs A and B; between the March and April runs of the standard vehicle, where there was no known change other than the 2000 lb higher inertia of runs B. The latter test with some 8% higher inertia, returned a fuel economy 3.9% lower than the former test. This reduced fuel economy was accompanied by a 25% increase in particulate emissions and an almost 30% increase in CO.

The most directly comparable runs, therefore, are those made on the same day, configurations B, C and D, Table I.

Slippage between tires and rolls has a strong influence on the quantity of energy captured by the Regenerative Power Train, and in consequence, the fuel economy and emissions performance of a vehicle so equipped. Inconspicuous tire slippage occurred during some of these tests, notably with configuration D. Test configurations C and D differed only in the manner in which the bus was installed on the dynamometer rolls, as discussed further in Appendix I. Large differences in performance are none-the-less very evident per table I. The results obtained with configuration D are valid in the sense that they relate actual emissions levels to actual vehicle fuel economy. On account of the tire slippage, configuration D may be considered to represent simply a less effective energy capture process. The results obtained using configuration D may therefore legitimately be used for trend analysis and are for this reason, included in the plots shown in figures 4 to 7.

Table I CBD Mileage and Exhaust Emissions Measurements.

Vehicle Configuration (& test date)	Mileage MPG(U.S) [l/100km]	CO	NOx	HC	Particulates.
		grams per mile [grams per km]			
A 88.3.22					
Std vehicle	4.08	13.92	40.11	4.17	1.28
I=25000 lb	4.11	12.51	41.79	4.14	1.44
mean	4.10 [57.44]	13.22 [8.21]	40.95 [25.44]	4.16 [2.58]	1.36 [.85]
B 88.4.21					
Std vehicle	3.90	16.94	41.45	4.28	1.76
	3.97	17.39	42.49	4.40	1.64
I=27000 lb					
mean	3.94 [59.78]	17.16 [10.67]	41.97 [26.08]	4.34 [2.70]	1.70 [1.06]
C * 88.4.21					
Regeneration	4.65	6.82	34.11	3.96	1.16
	4.67	7.06	33.80	4.02	1.34
I=27000 lb					
mean	4.66 [50.48]	6.94 [4.31]	33.96 [21.10]	3.99 [2.48]	1.25 [0.78]
D 88.4.21					
Intermediate result with Regeneration.	4.45	6.56	36.76	4.01	1.42
	4.54	6.67	36.09	4.03	1.48
I=27000 lb.					
mean	4.50 [52.33]	6.62 [4.11]	36.43 [22.63]	4.02 [2.50]	1.45 [0.90]

* Front vehicle restraint - Appendices I and II

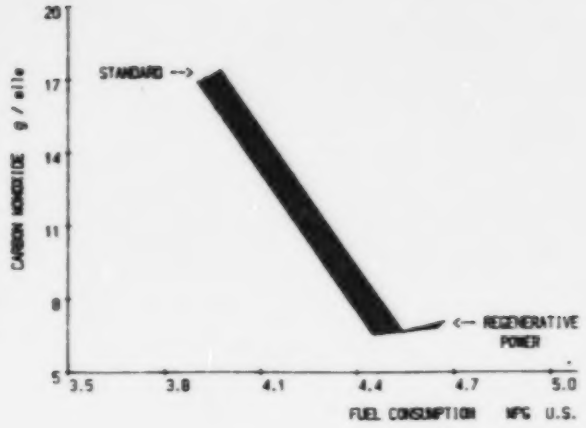

FIG. 4 CARBON MONOXIDE

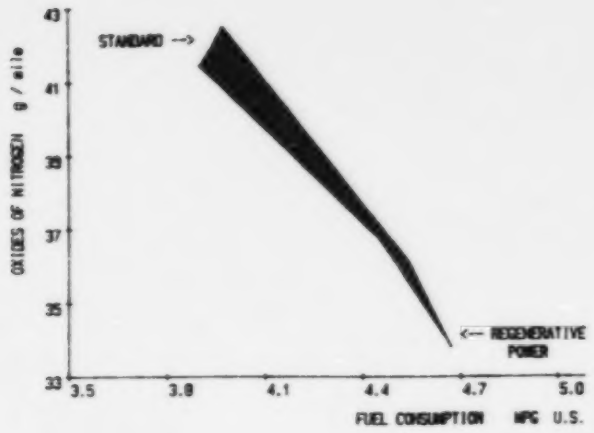

FIG. 5 OXIDES OF NITROGEN

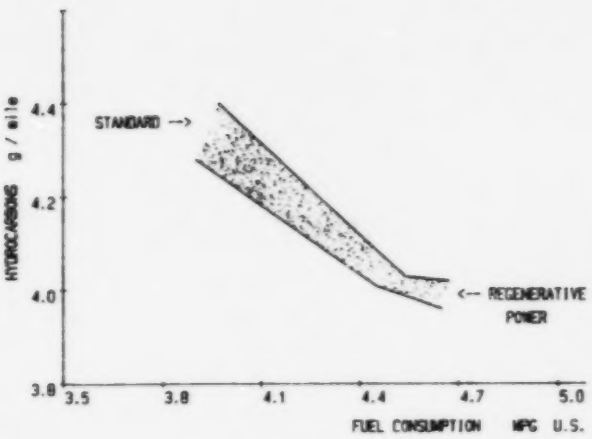

FIG. 6 HYDROCARBONS

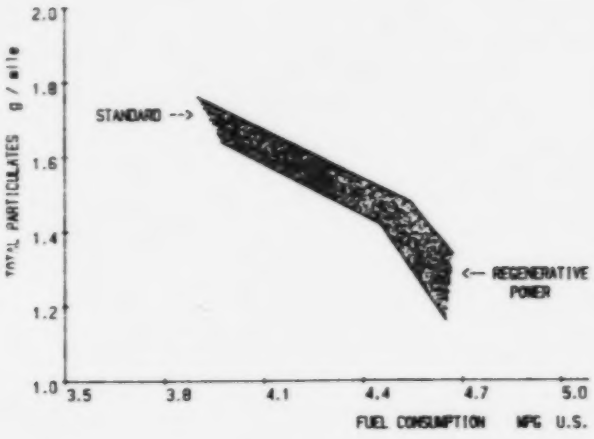

FIG. 7 TOTAL PARTICULATES

The plots utilise the data in Table I to show the test repeatability, of the three configurations B, C and D.

The changes in slope, seen in figures 4 to 7, suggest that NOx and particulate emissions would show increasing sensitivity to further fuel economy improvements, whereas HC and CO would be relatively less sensitive to further fuel economy improvements.

The effect of the vehicle tethering method and test repeatability, are covered in more detail within Appendix II.

In the case of the CBD cycle, the mean fuel economy figure obtained on the chassis dynamometer, with the standard vehicle configuration, is higher than the equivalent track test figure by 3.1% despite a weight disadvantage of 2.4% - table III. It must be noted that the dynamometer was loaded according to relationships developed for trucks and buses at generally higher road speeds than those used here, and that more than 18 months had elapsed since the regenerative bus road tests; making direct comparison difficult.

The fuel economy improvement, attributable to the use of the Regenerative Power system, using the chassis dynamometer, was 13.8%. This was lower than the track test result of 20%, using the 2000 lb weight difference between 'Standard' and 'Regenerative Power' configurations. (Configuration C compared with configuration A)

Configurations B and C differ in the application of the regenerative braking system and the method of vehicle restraint. As can be seen in tables I & II, an 18.4% improvement in fuel economy, was accompanied by reductions of 59.6% CO, 19.1% NOx, 8.1% HC and 26.5% particulate emissions.

The generation of particulate emissions and CO are evidently, most strongly influenced by the vehicle fuel economy, whereas NOx and HC emissions are less strongly influenced.

Table II CBD Mileage and Exhaust Emissions - Comparisons.

COMPARISONS	Mileage	CO	NOx	HC	Particulates
Test Repeatibility {Note. B 8% extra weight}					
B as % of A	96.1 %	129.8%	102.5%	104 %	125 %
Net Change	-3.9 %	+29.8%	+2.5 %	+4.3%	+25%
Effect of Regeneration.					
C as % of B	118.4%	40.4%	80.9%	91.9%	73.5%
Net change	+18.4%	-59.6%	-19.1%	-8.1 %	-26.5%

Table III CBD Mileage comparison-Chassis dyno & Track test.

[Track test mileage figures from reference (1)]

	Track test July '86	Chassis dyno. April '88	difference [dyno > track]
STANDARD BUS			
Test weight lbs	26380	27000	+2.4 %
CBD fuel economy MPG(U.S.)	3.82	3.94	+3.1 %
[1/100km]	[61.70]	[59.78]	"
REGENERATIVE BUS			
Test weight lbs	28360	27000	-4.8 %
CBD fuel economy MPG(U.S.)	4.59	4.66	+1.5 %
[1/100km]	[51.20]	[50.48]	"
FUEL ECONOMY GAIN	20 %	18 %	

In comparison with a previously tested bus, equipped with a DDA 6V-92 TA engine, (3) typical of U.S. (as opposed to Canadian) buses; operation of this bus, on a CBD cycle, in the 'standard' (as built) configuration, produced NOx levels approximately 50% higher, and particulate levels 60% lower; reflecting the different emission regulations previously in force and demonstrating the NOx versus particulate, trade off phenomenon accompanying injection timing changes.

CONCLUSIONS

During transient operations typical of city bus driving conditions, a strong relationship of decreasing diesel combustion emissions with increasing fuel economy, was demonstrated. This was most strikingly observed in the case of CO and particulates, which in general were observed to be the most sensitive to operating changes.

Table IV

Ambient conditions for chassis dyno. tests.

	Configuration A March 22 1988	Configuration B,C,D April 21 1988
Pressure mm Hg	741.08	733.81
Humidity %	38	50
Dry bulb temp. C	28.9	26.1

The results obtained, using the prototype Regenerative Power System, demonstrate the potential for the reduction of all the regulated emissions.

Relatively minor design changes to the Regenerative Power Train system are projected to enhance the performance improvement from the 20% fuel economy improvement of the current prototype system, to 25% (when operating on the 20 mph CBD and similar 30 mph cycles). Using an enhanced system, due to the increasing sensitivity to fuel economy suggested by these results, NOx and particulate emissions may be expected to decline, to an even greater extent.

Simply engaging the Regenerative Power System, with no changes to dynamometer, inertia settings or vehicle powerplant; an 18% improvement in fuel economy is accompanied by a 60% reduction of CO and a 27% reduction in particulate emissions. [Table II case C versus B]

The impacts that vehicle weight and power train efficiency have on fuel economy and pollutant emissions; are particularly significant in the case of city buses, due to the highly transient operation of these vehicles. This suggests that for regulatory purposes, it is the total vehicle that should be considered, rather than the engine exclusively.

ACKNOWLEDGEMENTS

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Appendix I

Dynamometer roll slippage and its reduction.

The dynamometer rolls comprise one pair of 8 5/8" diameter rolls to support the twin tires on each side of the rear axle. Under static conditions the weight is evenly divided between the two rolls of a pair. Of these two rolls, one only is connected to a dynamometer which is used to apply a load corresponding to rolling resistance and air drag. This same roll is connected also to the inertia discs which apply the inertial loading during acceleration and braking. The second roll of the pair rotates quite independently. It is used to support part of the tire weight and to locate the vehicle axially, but is otherwise inactive.

Under the braking conditions of the test cycles used, severe slippage between tires and rolls was observed on occasion. In comparison with the 'on road' situation, one has here a

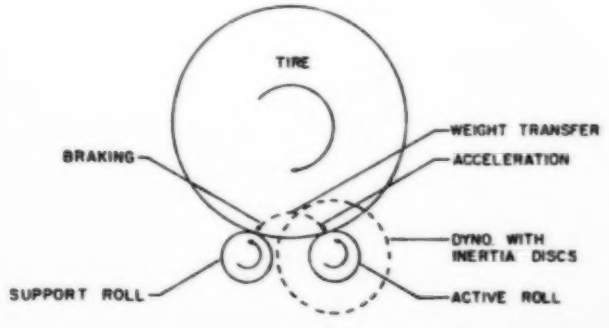

FIG. 8 WEIGHT TRANSFER BETWEEN DYNO. ROLLS

Table A2 Repeatibility and tethering effects.

(Note: all values below are the average of two repeat runs made consecutively)

COMPARISONS	Mileage	CO	NOx	HC	Particulates
Same config. Different day					
1 - 25R	4.1	13.22	40.95	4.16	1.36
2 - 25R	4.15	6.43	40.48	4.07	1.17
% Change	-1.2 %	+106 %	+1.16 %	+2.2 %	+16.24 %
Front & rear tethering					
2 - 25F	4.35	5.81	39.85	4.05	1.17
2 - 25R	4.15	6.43	40.48	4.07	1.17
% Change	+4.6 %	-9.6 %	-1.56 %	- .49 %	+0.0 %

smaller contact area, a lower coefficient of friction and, because of the weight being split between two rollers, a lower normal force at the contact patch between the surfaces transmitting the tractive effort.

In addition, during retardation, where the road wheel is decelerating the dynamometer rolls; the road wheel tends to move axially backwards, further reducing the weight on the active roll fig. 8.

Attempts to remedy the tire slippage using a proprietary friction enhancer, as used by drag racers, was only partially successful. Slippage was effectively reduced by the expedient of applying a static axial load to the front of the bus, tending to pull the bus toward the forward rolls, thereby forcing a larger proportion of the vehicle weight onto the active rolls.

APPENDIX II

Effect of vehicle restraint arrangements.

Subsequent to the tests presented in the main body of the paper, S.W.R.I. staff investigated further, the effect of changes in vehicle restraint, by applying the same kind of changes to the standard vehicle.

The results again demonstrated relatively large variations in CO and particulate levels on different days, and interestingly, demonstrated a consistent mileage improvement when the restraint was applied at the front end of the vehicle. In general the manner of tethering had little impact on the emissions levels recorded - Table A2. The conclusions drawn from these observations are:-

1. Where the manner of tethering imposes additional loads or tire deformation, an increase in tire rolling resistance will occur, adversely affecting the vehicle mileage. Tethering of a test vehicle is preferably applied adjacent to a non-rotating axle.
2. In the case of the subject tests, the change to front tethering had two effects; to reduce the tire rolling resistance, and to reduce the tire slippage under braking.